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Cornucopia or curse? Reviewing the costs and benefits of shale gas hydraulic fracturing (fracking)

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ABSTRACT

This study assesses the overall technical, economic, environmental, and social costs and benefits of the hydraulic fracturing ("fracking") of natural gas. Drawn from a review of more than 100 studies looking at shale gas in the past 10 years, most of them peer-reviewed, this article begins by briefly explaining the process of hydrofracking and summarizing recent market trends up until late 2013. Then, the study discusses a series of advantages and disadvantages to hydrofracking. It notes that done properly, shale gas development can enhance energy security and the availability of energy fuels, lower natural gas prices, offer a cleaner environmental footprint than some other fossil fuels, and enable local economic development. However, done poorly production can be prone to accidents and leakage, contribute to environmental degradation, induce earthquakes, and, when externalities are accounted for, produce more net economic losses than profits. The study concludes that the pursuit and utilization of shale gas thus presents policymakers, planners, and investors with a series of pernicious tradeoffs and tough choices.

Contents

1. Introduction

To understand the contestable nature of hydrofracking, consider two anecdotes from Pennsylvania. In 2012, the state issued permits for 2484 "unconventional" natural gas wells, with 1365 of them drilled, and Pennsylvanians earned some $1.2 billion in

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royalties that year [24]. The locals of Smithfield, Pennsylvania supported fracking to the degree that they named their local food delicacy the "frack burger". This fervor for fracking, nonetheless, differed greatly from that of a community near Pittsburg, Pennsylvania, where shale gas production has transformed once-clear streams into muddy-swamps full of dead fish and flammable water. One resident complained that shale gas production was a scourge on his family's health that just "refuses to go away" [28].

Which picture of shale gas development—cornucopia or curse—is the true one? This study finds that they both are. It presents the results of a qualitative review of articles discussing shale gas and hydraulic fracturing, drawn mostly from the peer-reviewed energy studies literature, published in the past 10 years. On the one hand, this review finds that shale gas production, done properly, can bring with it wide-ranging benefits including the enhancement of energy security, lower natural gas prices, a cleaner environmental footprint than some other fossil fuels, and economic development. On the other hand, it finds that done poorly, it can be prone to accidents and leakage, contribute to environmental degradation, induce earthquakes, and, when externalities are accounted for, produce more net economic costs than benefits. This means that "hydraulic fracturing and horizontal drilling of shale gas plays is fraught with contention" [80], and that "heated debate continues as to whether the economic and energy benefits associated with shale gas extraction are worth the potential environmental impacts" [79].

To contribute to the debate, this study surveys and summarizes a large number of shale gas assessments published over the past decade to document its pros and cons, following a comprehensive "literature review" format commonly utilized in the social sciences [15,8,113] and applied frequently in the energy studies literature [16,94,96]. This article begins by briefly explaining the process of hydrofracking, describing how the technology works, and summarizing recent market trends up until late 2013. Then, it discusses a series of advantages and disadvantages to hydrofracking before offering a series of conclusions for energy planners, investors, and analysts.

2. Shale gas basics

Despite the claim that we are entering a new "shale gas revolution," its production does have a long history. In 1821, decades before the first oil well was drilled, commercial shale gas was extracted in Fredonia, New York. The United Kingdom's first well to encounter shale gas was drilled into the Upper Jurassic Kimmeridge Clay in 1875. In the Williston Basin in the United States, Bakken Shale has produced shale gas since 1953, and in 1969 the Atomic Energy Commission detonated an atomic bomb underground in Western Colorado to test "nuclear stimulation technology" that successfully "liberated natural gas that had been trapped in shale formations 7000 feet deep" [49]. In 1976, the U.S. Department of Energy initiated the Eastern Gas Shales Project at a cost of $200 million and the Mitchell Energy and Development Corporation (since merged with Devon Energy Corporation) started producing gas from the Barnett Shale of the Fort Worth Basin in 1981 [9,91]. As the success of Mitchell Energy and Development became apparent, other companies aggressively began fracking so that by 2005, the Barnett Shale alone was producing almost half a trillion cubic feet per year of natural gas [106]. In the United States, shale gas production has grown from a meager 0.2 trillion cubic feet in 1998 to an enormous 4.9 trillion cubic feet in 2010 [32].

But for readers unfamiliar with shale gas production, this all begs the question: what exactly is it? Natural gas comes in a variety of hydrocarbon mixtures located in a variety of geological settings. What engineers call "wet gas" has a higher proportion of heavier molecules like ethane, propane, butane, and pentane, and comes in a liquid state; "dry gas" comes in gaseous state and (in the current market) fetches a lower price. Most "wet" and "dry" gas comes from "plays" (the industry term for "fields") composed of well-defined reservoirs with high rates of permeability. "Unconventional gas" refers to six types of gas plays where permeability is low: Coal-bed methane (contained in coal seams); tight gas (gas in low permeable formations); geo pressured gas (gas trapped in deep high-pressured reservoirs); gas hydrates (methane in the form of a crystalline solid that can be found in marine sediments); shale gas (gas trapped within shale formations of sedimentary rocks); and ultra-deep gas (offshore reservoirs locked in high depths) [7,47,110].

The phrase "shale gas" therefore refers to natural gas extracted from gas shales, porous rocks that hold gas in pockets with the characteristics summarized in Table 1. Though the technology of shale gas production continues to improve, Ridley [83] notes that it involves at least seven elemental steps or phases:

- Seismic exploration refers to when underground rock formations are mapped using sound waves and three-dimensional reconstruction to identify the depth and thickness of appropriate shales. This may be done from the air, desktop (reanalysis of older data) or ground surveys;
- Pad construction refers to when a platform for a drilling rig is leveled and positioned over a discovered play, typically occupying about 5 acres (2 ha);

Table 1
Major characteristics of shale gas.
Source: Zou [114].

Geological characteristics	Integrated source rock and reservoir, early reservoir formation, continuous accumulation, no obvious trap boundary, sealing or caprock is necessary Tight reservoirs with natural gas stored in an absorbed gas and free gas pattern Not controlled by structure, continuous and large areas of distribution, same area as effective gas-generation source rock Large resource potential with local "sweet spot" core areas
Mineral characteristics	Greater than 2 percent non-residual organic carbon Brittle mineral (e.g. quartz) content over 40 percent and clay mineral content less than 30 percent Maturity of dark organic-rich shale is more than 1.1 percent Air porosity is more than 2 percent, permeability is more than $0.0001 \times 10^3\ \mu m^2$ Effective thickness of organic-rich shale over 30–50 m
Development characteristics	Low individual well production cycle and long field production cycle Non-Darcy flows of production with lower recovery ratios Requires horizontal wells, multistage fracturing, micro-seismic and other advanced technologies to implement reservoir stimulation treatment

- Vertical drilling refers to when a small drilling derrick drills as many as a dozen holes down to the shale rock, encasing a borehole in five concentric sleeves of steel and concrete near the surface, falling to one sleeve as the depth increases (suitable shales are typically 4000–12,000 feet, or 1220–3660 m, below the surface);
- Horizontal drilling refers to when a larger drilling derrick, 150 feet (46 m) high, is assembled on site and slant-drills each well horizontally into the shale formation for thousands of feet in different directions, using gas sensors to ensure it stays within the seam;
- Hydraulic fracturing refers to when the concrete casing of the horizontal pipe is perforated with small explosive charges and water mixed with sand and other proppants is pumped through the holes at 5000 psi (pounds per square inch) to fracture the rock with hairline cracks up to 1000 feet (305 m) from the pipe, taking 3–10 days for a single "frack" job;
- Sustained production refers to when a "Christmas tree" valve assembly about the size of a garden shed, and a set of small tanks about the size of a small garage, remains on site to collect gas (and small quantities of oil), which then flows through underground pipes to a large compressor station serving a large number of wellheads and onwards to trunk pipelines;
- Waste disposal refers to when tanks collect water that flows back out of the well. The water is generally reused in future fracking, or desalinated and disposed of through sewage and wastewater systems.

Arguably the most important, and novel, parts of this process are hydraulic fracturing and horizontal drilling. The key characteristic distinguishing shale gas from conventional gas is that it does not naturally flow into a well. It can be made to flow, however, by fracturing the formation containing the gas, artificially increasing its permeability. This is accomplished by "hydraulic fracturing", or "fracking" for short [9,44]. Fracking involves drilling, often at great depth, down into the shale layer, and then pumping water sand and chemicals (called proppants) into the shale at high pressure, releasing natural gas that flows back up with the drilling fluids [19,70]. To access large shales or large amounts of gas, multi-stage fracking is typically utilized, where drillers not only use vertical wells but also horizontal ones, and they repeat the fracking process at each well as many as 20 times, with each pressurization fracturing a new region of the shale gas formation [36]. Depending on the size of the well, the fracking process can involve injecting millions of gallons of water combined with thousands of gallons of the proppants shown in Table 2.

When viewing Table 2, it is important to note that the specific chemical composition of proppants will vary according to the unique attributes of each site. Also, the constituents depicted in Table 1 are rarely utilized simultaneously; most producers will use only three to four employed at a time. During the first few weeks of fracturing, known as the "flowback period," as much as 10–40 percent of the fracturing fluid will return to the surface. Once active gas production begins, wastewater, known as produced water, rises out of the well with concentrations of chemicals shown in Table 3, though its specific attributes will, again, vary based on length of operation as well as whether there are multiple wells or a single well.

Geologists have known of the existence of shale gas for more than a century, but it was long considered difficult to extract at a reasonable cost. What has changed over the last few decades is the recognition that the combination of (multiple) fracking and horizontal drilling can sufficiently raise the permeability of the formations holding these resources to liberate a large quantity of gas, and this at a price competitive with conventional gas exploitation [41,70,104]. Indeed, less than 2 percent of the well fractures since the 1940s have utilized the high-volume technology available today to transform shale into gas [38].

This combination of advances in multi-stage fracking and horizontal drilling have led many commentators and analysts to proclaim an eminent "shale gas revolution." British Petroleum, for instance, expects global shale gas production to grow sixfold from 2011 to 2030 [41]. Shale gas production in the United States already accounts for roughly 30 percent of the nationwide total—a growth rate up from only 4 percent in 2005 [60]. Fig. 1 illustrates that shale gas production from the largest plays in the country has grown from less than 1 billion cubic feet per day in 2000 to almost 12 billion cubic feet in 2012, making the U.S. a net exporter of natural gas in 2009; the supply of shale gas is anticipated to double again by 2015 and triple by 2030 [18,114]. According to the

Table 3
Typical range of concentrations for common constituents of flowback water from natural gas development in the Marcellus Shale Formation.
Source: Gregory et al. [32].

Constituent	Single well (early) (mg/L)	Single well (late) (mg/L)	Multiple wells (late) (mg/L)
Total dissolved solids	66,000	150,000	261,000
Total suspended solids	27	380	3200
Hardness (as $CaCO_3$)	9100	29,000	55,000
Alkalinity (as $CaCO_3$)	200	200	1100
Chloride	32,000	76,000	148,000
Sulfate	5	7	500
Sodium	18,000	33,000	44,000
Calcium, total	3000	9800	31,000
Strontium, total	1400	2100	6800
Barium, total	2300	3300	4700
Bromide	720	1200	1600
Iron, total	25	48	55
Manganese, total	3	7	7
Oil and grease	10	18	260

Table 2
Volumetric composition and purposes of the typical constituents of hydraulic fracturing fluid.
Source: Gregory et al. [32].

Constituent	Composition by volume (%)	Example	Purpose
Water and sand	99.50	Sand suspension	"Proppant" sand grains hold microfractures open
Acid	0.123	Hydrochloric or muriatic acid	Dissolves minerals and initiates cracks in the rock
Friction reducer	0.088	Polyacrylamide or mineral oil	Minimizes friction between the fluid and the pipe
Surfactant	0.085	Isopropanol	Increases the viscosity of the fracture fluid
Salt	0.06	Potassium chloride	Creates a brine carrier fluid
Scale inhibitor	0.043	Ethylene glycol	Prevents scale deposits in pipes
pH-adjusting agent	0.011	Sodium or potassium carbonate	Maintains effectiveness of chemical additives
Iron control	0.004	Citric acid	Prevents precipitation of metal oxides
Corrosion inhibitor	0.002	*n,n*-Dimethyl formamide	Prevents pipe corrosion
Biocide	0.001	Glutaraldehyde	Minimizes growth of corrosive and toxic bacteria

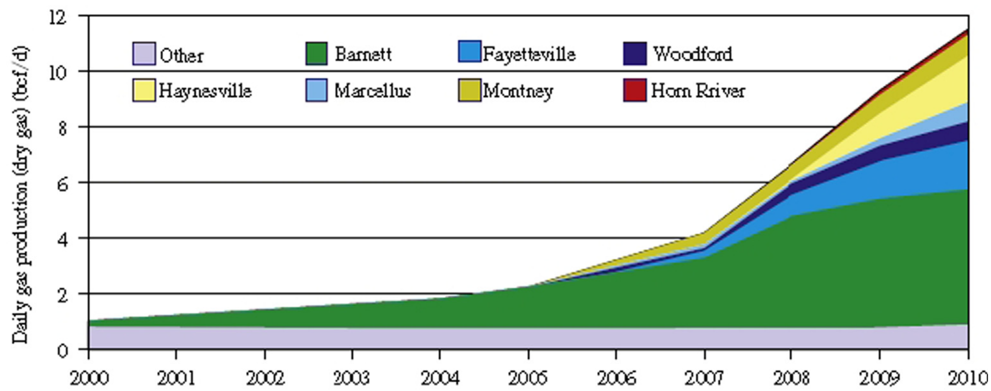

Fig. 1. Shale gas production from major plays in the United States, 2000–2010 (billion cubic feet per day).
Source: Zou [114].

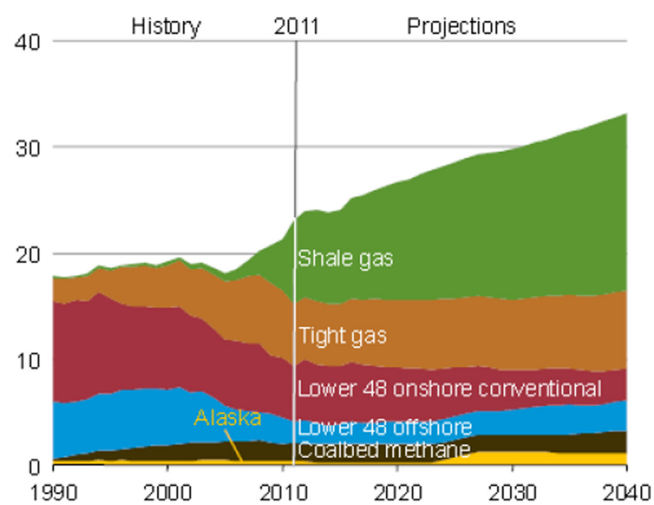

Fig. 2. Natural Gas Production in the United States by Source, 1990 to 2040 (trillion cubic feet per year).
Source: U.S. Energy Information Administration [107].

U.S. Energy Information Administration, shale gas will account for almost 50 percent of national domestic gas production by 2030, numbers reflected in Fig. 2. The media as a result have begun discussions about "Saudi America" and how it will be able to shape global energy markets as a major net exporter. The Citi Group even boldly published a report in 2012 with the provocative title "Energy 2020: North America, the new Middle East?"

In all likelihood, major shale gas production will not be confined to the United States. The International Energy Agency [44] expects the production of unconventional gas, primarily from shales, to more than triple from today to 2035, growing to account for 32 percent of global production that same year, with Australia, Canada, China, the European Union, India, Indonesia, and Russia joining the United States as substantial producers. Put another way, the International Energy Agency expects that $6.9 trillion will be invested in shale gas infrastructure over this period and that more than one million new wells—twice the total in the US—will be required. It is estimated that 80 percent of natural gas wells drilled in the next decade will employ hydraulic fracturing [88]. Based on these trends, European economist Bocora [7] writes that the "discovery of large deposits of shale gas triggered a quiet revolution … The rise of unconventional forms of oil and gas and a fast shift from the traditional producers to plentiful domestic resources could present the beginning of a new era in global energy affairs." Similarly, MIT Chemistry Professor Deutch [18] calls the "dramatic increase in estimates of unconventional sources of natural gas" the "greatest shift in energy-reserve estimates in the last half century".

3. The pros of shale gas development

So what, then, is the fervor over shale gas about? This section of the paper presents four compelling reasons: its sheer ability to provide a widely available source of energy, its affordability, its cleaner environmental footprint than other fossil fuels, and the jobs and economic development production brings suppliers and exporters.

3.1. *Abundance of supply*

One seemingly obvious advantage to shale gas is that there is a lot of it. The U.S. EIA [106] assessed 48 shale gas basins around the world in 32 countries, containing almost 70 shale formations, and concluded that the international resource was "vast," with proven reserves amounting to almost the same level as conventional natural gas. Fig. 3 illustrates that the three largest energy consumers in the world, China, the European Union, and the United States, also have extensive shale gas deposits, fortuitously matching abundance in supply with abundance in demand. Taken together, the EIA estimated that the 48 shale gas basins they assessed had more than 5760 trillion cubic feet of recoverable gas—numbers broken down by Table 4.

To put some of these numbers in perspective, the Marcellus Shale, located in western New York, Pennsylvania, and Ohio, is thought to have natural gas supply equivalent to 45 years of U.S. national consumption; its reserves would be worth $500 billion at 2011 prices [27]. According to IHS, a business-information company, estimated recoverable shale gas could amount to about 42 trillion cubic meters, almost equal to the total conventional gas discovered in the United States over the past 150 years, and equal to about 65 times current U.S. annual consumption [26]. Because of these plentiful reserves, Joseph Stanislaw, a senior energy adviser to Deloitte LLP, stated recently that "global shale will happen and when it does begin, it will take off with the same force we've seen in the U.S." ([92, p. 2]). Others have pointed out that the increased availability of natural gas induced by fracking could "revitalize the chemical industry" since cheap natural gas is needed to manufacture a variety of products such as plastic, agrochemicals, and pharmaceuticals, and increase the supply of fertilizer, ensuring the availability of food and reducing pressure on the conversion of forests to agricultural farms [83].

3.2. *Lower natural gas prices*

Another advantage, connected in part to the availability of shale gas, is its affordability. Although the average cost of shale gas production will vary from site to site, it tends to range from $2 to $3 per thousand cubic feet of gas, about 50–66 percent cheaper than

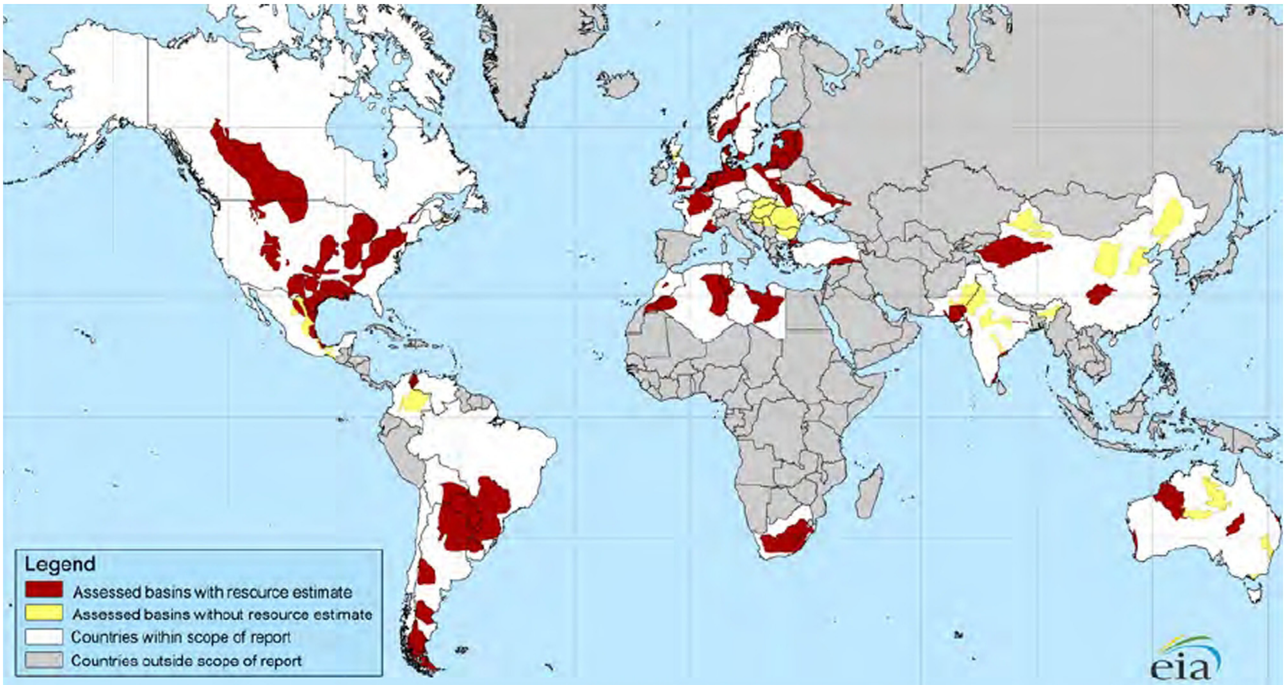

Fig. 3. Map of 48 major shale gas basins in 32 countries.
Source: U.S. EIA [106].

production from new conventional gas wells, and technological learning could drive costs down further [18]. The United States is already producing such a large amount of shale gas that natural gas prices have plummeted from $13 per million BTUs to $1 to $2 in 2012. This cheap gas has translated into "cheap electricity" with American factories paying half the going rate for electricity in Chile or Mexico, and in New York prices were the lowest they have ever been since the state developed a wholesale market in 1999 [24]. Globally, this has meant that shale gas has depressed natural gas prices in the United States significantly compared to other major markets, a trend illustrated in Fig. 4. Fig. 5 shows that, without shale gas development, anticipated natural gas prices could be more than 2.5 times higher than they otherwise would be by 2050 [48].

The full development of commercial shale gas therefore has the potential to do wonders for depressing global prices of natural gas and facilitating global competition and geopolitical shifts that break longstanding monopolies. Greater shale gas production could lesson European dependence on Russian gas, reducing Russia's ability to leverage higher prices [18]. Moreover, researchers from Rice University have projected that accelerated global shale gas production could lower prices in Asia as state-run gas monopolies lower prices to match cheap natural gas emanating from North America and a more open, competitive market [65,66].

3.3. Cleaner environmental footprint

Though shale gas has some negative environmental attributes discussed below in the section of the paper on "cons," it does have a cleaner environmental footprint than other fossil fuels, mainly oil and coal. Shale gas has lower emissions of sulfur oxides, nitrogen oxides, and mercury than coal and oil. It also has carbon benefits as well [11]. As one study in *Nature* put it:

> *Global warming is a serious issue that fracking-related gas production can help to alleviate. In a world in which productivity is closely linked to energy expenditure, fracking will be vital to global economic stability until renewable or nuclear energy carry more of the workload … Replacing coal with natural gas in power plants, for example, reduces the plants' greenhouse emissions by up to 50%* [26].

The use of shale gas has thus lowered the overall emissions intensity of the US national grid (heavily dependent on coal), and will continue to lower emissions to the extent that coal- or oil-fired generation is displaced. Researchers at MIT, for instance, compared future electricity scenarios for the United States with and without accelerated shale gas use, and noted that the shale gas scenario would reduce national emissions from the electricity sector 17 percent compared to business as usual [47]. Other studies have reached similar results [3,49,60].

To be sure, the resurgence of natural gas has wrought real environmental benefits. As Vermont Law School scholars Parenteau and Barnes [78] explain:

> *This surge of natural gas has benefited the environment and public health. Low natural gas prices have dramatically altered the energy mix in the electricity sector, particularly with respect to coal—the dirtiest fuel that imposes the highest social costs. One result of displacing all of this coal is that United States carbon emissions are, for now at least, the lowest they have been in twenty years Historically, coal supplied almost half of the nation's electricity. Yet as of April, 2012, natural gas and coal were virtually tied, with each providing thirty-two percent of total generation. Dozens of existing coal plants have been shuttered, and over a hundred new plants have been cancelled.*

In essence, the entrance of shale gas has driven out a far dirtier fuel, coal, from the electricity sector. Indeed, as an annual share of United States fossil-fuel fired electric power generation, natural gas was practically equal to coal in 2012, as Fig. 6 shows.

Because of these comparative environmental benefits, many commentators have argued that shale gas is the best way for the United States, and other countries, to meet their greenhouse gas reduction goals. William Press, a member of the president's Council of Advisors on Science and Technology in the U.S., writes

Table 4
Estimated shale gas technically recoverable resources for select basins, 2011.
Source: [106].

	2009 Natural Gas Market **(trillion cubic feet, dry basis)**			Proved Natural Gas Reserves **(trillion cubic feet)**	Technically Recoverable Shale Gas Resources **(trillion cubic feet)**
	Production	**Consumption**	**Imports (Exports)**		
Europe					
France	0.03	1.73	98%	0.2	180
Germany	0.51	3.27	84%	6.2	8
Netherlands	2.79	1.72	(62%)	49.0	17
Norway	3.65	0.16	(2,156%)	72.0	83
U.K.	2.09	3.11	33%	9.0	20
Denmark	0.30	0.16	(91%)	2.1	23
Sweden	–	0.04	100%		41
Poland	0.21	0.58	64%	5.8	187
Turkey	0.03	1.24	98%	0.2	15
Ukraine	0.72	1.56	54%	39.0	42
Lithuania	–	0.10	100%		4
Others	0.48	0.95	50%	2.71	19
North America					
United States	20.6	22.8	10%	272.5	862
Canada	5.63	3.01	(87%)	62.0	388
Mexico	1.77	2.15	18%	12.0	681
Asia					
China	2.93	3.08	5%	107.0	1,275
India	1.43	1.87	24%	37.9	63
Pakistan	1.36	1.36	–	29.7	51
Australia	1.67	1.09	(52%)	110.0	396
Africa					
South Africa	0.07	0.19	63%	–	485
Libya	0.56	0.21	(165%)	54.7	290
Tunisia	0.13	0.17	26%	2.3	18
Algeria	2.88	1.02	(183%)	159.0	231
Morocco	0.00	0.02	90%	0.1	11
Western Sahara	–	–		–	7
Mauritania	–			1.0	0
South America					
Venezuela	0.65	0.71	9%	178.9	11
Colombia	0.37	0.31	(21%)	4.0	19
Argentina	1.46	1.52	4%	13.4	774
Brazil	0.36	0.66	45%	12.9	226
Chile	0.05	0.10	52%	3.5	64
Uruguay	–	0.00	100%		21
Paraguay	–	–			62
Bolivia	0.45	0.10	(346%)	26.5	48
Total of above areas	**53.1**	**55.0**	**(3%)**	**1274**	**6622**
Total world	**106.5**	**106.7**	**0%**	**6609**	

that "America will only achieve the ambitious climate change goals outlined by President Barack Obama … by encouraging wide-scale fracking for natural gas over the next few years" (quoted in [64]).

3.4. Economic development

A final benefit to shale gas is the economic development—the employment, jobs, infrastructure, revenues, and taxes—it promises. For instance, from 2000 to 2008, the number of active shale gas wells drilled in the state of New York almost doubled from 6800 to 13,600, with 80,000 wells over the next decade expected; in Pennsylvania, the state's 350,000 active wells are anticipated to grow by another 300,000 [27]. Pennsylvania saw its shale gas boom create 29,000 new jobs in 2008 with revenues of $2.3 billion and tax revenues for governments of $238 million [51]. In 2009 production on the Marcellus Shale across West Virginia and Pennsylvania brought $4.8 billion in gross regional product, generated 57,000 new jobs, and created $1.7 billion in local, state, and federal tax collections [90]. Production in Texas at the Barnett Shale have in 2011 accounted for $11.1 billion in annual output, or 8.1 percent of the entire region's economy, and 100,000 jobs, representing almost 10 percent of regional employment [36]. It is important to note that these numbers reflect only direct economic benefits; indirect ones from earlier studies assessing higher incomes and landowner royalties also occur, and are summarized in Table 5. Because of these benefits, the United States has even begun promoting fracking abroad through the Global Shale Gas Initiative, with its central justification being that "shale gas has been a terrific boon" to the communities adopting it [88].

4. The cons of shale gas development

Though many of the benefits of shale gas development are tangible, they also come with a sobering array of costs that include

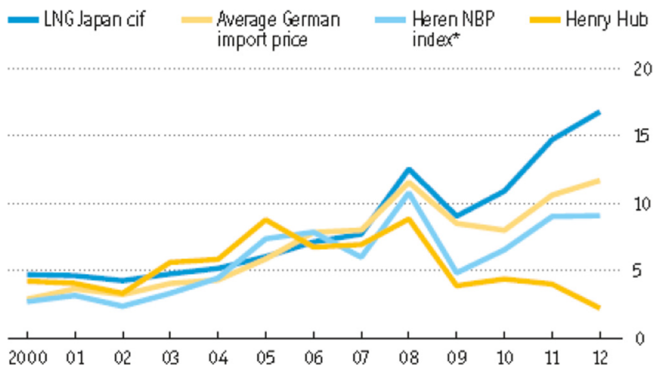

Fig. 4. Natural gas prices in Europe, Japan, and the United States, 2000–2012 ($ per million Btu).
Source: Economist [25].

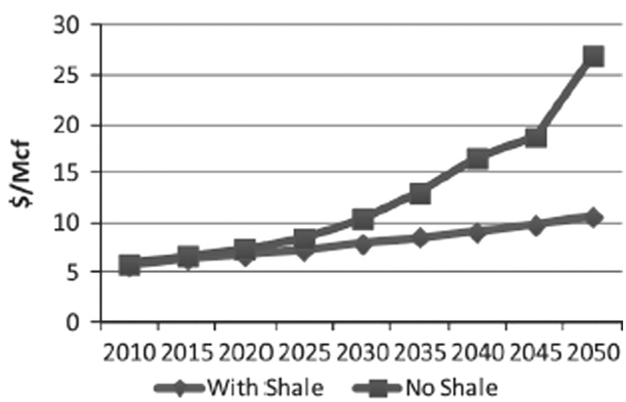

Fig. 5. Expected natural gas prices for the United States, 2010–2050.
Source: Jacoby et al. [48].

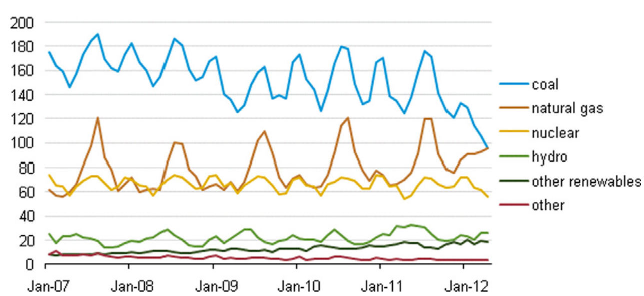

Fig. 6. Electricity power generation in the United States, 2007–2012 (million MWh).
Source: U.S. EIA.

a technological sophistication that makes drilling and fracking prone to accidents; the degradation of air, water, and land; enhanced risk of earthquakes and seismic events; and highly uncertain reserves with unclear profit margins. This section of the paper analyzes each in turn.

4.1. Technological sophistication

Shale gas production is technically complex, capitally intensive, and financially expensive—which contributes to the risk of cost overruns for projects, can lead to accidents and leakage, and may make future development contingent on uncertain technological breakthroughs in carbon capture and storage technology.

First, shale gas production is complicated; readers may recall the seven steps recounted in the "Shale Gas Basics" section of the paper. The process of fracking not only requires a greater deal of energy than conventional gas [98], it requires specialized equipment to manage depth and pressure with nonlinear cost curves. For instance, as much as 50 percent of the total drilling cost is consumed by drilling the last 10 percent of each hole [51]. A drill site covering two hectares quickly turns into a "heavy industrial zone," even if it's in suburban Fort Worth, Texas, with more than 100 large water tanker trucks coming and going each day to serve wells at a single site [52]. Shale gas extraction is incredibly site specific. As the U.S. Department of Energy [105] has noted:

> *Shale plays in different basins have different geological characteristics and occur in areas with very different water resources. In the Eagle Ford, in Texas, there is almost no flow-back water from an operating well following hydraulic fracturing, while in the Marcellus, primarily in Ohio, New York, Pennsylvania and West Virginia, the flow-back water is between 20 and 40 percent of the injected volume. This geological diversity means that engineering practice and regulatory oversight will differ widely among regions of the country.*

In Texas, for instance, wastewater can be managed by injecting it into deep wells that serve as natural depositories, but such formations do not exist in Pennsylvania or West Virginia, where wastewater must be pumped and treated externally [81]. Thus, as Fig. 7 shows, each shale play is unique—it has its particular composition of gas deposits and minerals, making the fracking process idiosyncratic [114]. It also makes shale gas production an expensive endeavor, with a typical horizontal well costing $3–$5 million, to say nothing about the costs of operating the well, leasing the land, and managing water and waste [51].

Second, poor operating practices and/or lax regulation can lead to shale gas leakage and accidents. Because shale gas production involves so many phases, it can be difficult to detect malfunctions. For instance, the National Oceanic and Atmospheric Administration spent several weeks collecting air samples over shale gas wells in Utah, and found that 6–12 percent of the Uinta Basin's natural gas production could be escaping into the atmosphere, far more than commonly estimated [61]. Holzman [35] also reports that 50 percent of new natural gas wells recently inspected in Quebec leaked methane. Researchers from the National Renewable Energy Laboratory analyzed more than 16,000 sources of air-pollutant emissions reported in a Texas inventory of the upstream and midstream natural gas industry and noted that "more than half" had leakage from tanks and vents, and that an estimated 1.5% of Barnett Shale produced gas was emitted to the atmosphere before reaching the power plant with an additional 5.6% of produced gas consumed along the supply chain [60]. Scientists from the National Oceanic and Atmospheric Administration and the University of Colorado, Boulder, have also documented that shale gas production in the Denver-Julesburg Basin is losing about 4% of its gas to the atmosphere—not including additional losses in the pipeline and distribution system [103]. Other studies have noted that 3.6–7.9 percent of methane from shale gas production escapes to the atmosphere due to venting and leaks [37].

These leaks can lead to serious accidents (for more on the climate change implications of these leaks, read the section below on "environmental degradation.") In June of 2010, Houston-based EOG Resources had a blowout at a Clearfield County, Pennsylvania well that discharged 35,000 gallons of fracking fluid into a state forest. In Caddo Parish, Louisiana, fracking fluid leaked from a well pad into an adjacent pasture, causing the death of seventeen cattle in 2009, and dozens of similar accidents and leaks have been recorded in four other states [80]. Accidents can occur not only at shale gas sites, but pipelines. Amarillo, Texas, saw a natural gas pipeline connected to shale gas wells explode in 2009 with the force of a magnitude 4 earthquake, burning at temperatures in excess of 3800 °C and sending a column of flame into the air more than 60 m high. These incidents do not bode well for the future of

Table 5
Direct and indirect economic benefits from shale gas production in the United States.
Source: Kinnaman [56].

Shale play	Estimated impact	In the year	To the economy of	Assumptions
Marcellus	$4.2B in output 48,000 jobs	2009	Pennsylvania	100% royalties spent immediately; 95% of direct spending in state
Marcellus	$8.04B in revenues 88,588 jobs	2010	Pennsylvania	100% royalties spent immediately; 95% of direct spending in state
Barnett	$11B in revenues 111,131 jobs	2008	Dallas/Ft worth area	The amounts were fully adjusted to reflect those funds that are paid outside the region (and state) and are further reduced to account for out-of-area spending, savings, and taxes
Hayensville	$2.4B in revenues 32,742 jobs	2008	Louisiana	All direct spending in state, assumes households spend 5% of lease and royalty payments in 2008
Fayetteville	$2.6B in revenues 9533 jobs	2007	Arkansas	Survey asks firms to report state of residence of employers, but not whether spending occurs in state or out of state
Marcellus	$760M in revenues 810 jobs	2000 Wells over 10 year period	Broome County, NY	Assumptions regarding percentage of drill spending in local economy not stated
Marcellus	$2.06B in revenues 2200 jobs	Gas production per year	Broome County, NY	Assumes 15% of royalty earnings remain in local economy

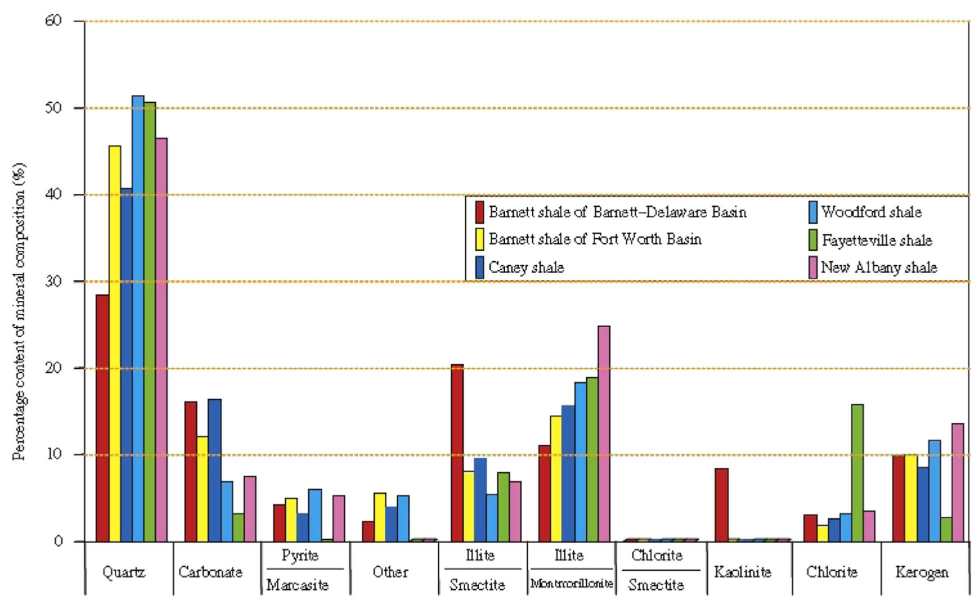

Fig. 7. Mineral composition of major shale gas plays in the United States.
Source: Zou [114].

shale gas, given that one study looking at major energy accidents from 1907 to 2007 concluded that natural gas pipelines were the type of energy infrastructure most frequent to fail, accounting for 33 percent of all major energy accidents worldwide [93]. Researchers at the Paul Scherrer Institute similarly collected data on industrial accidents from 1945 to 1996 and concluded that 31 percent of these accidents were related to the energy sector, with the “riskiest” stages when hydrocarbons were being distributed through regional pipelines and trucks or transported to refineries [34]—both stages prevalent in shale gas production.

Third, truly low-carbon shale gas development is contingent on future technological breakthroughs that have yet to occur. One peer-reviewed study argued that shale gas can play a major role in reducing greenhouse gases only if large-scale carbon capture and sequestration technology can be successfully developed [109]. Levi [59] from the Council on Foreign Relations has also written that “absent carbon capture and sequestration, a natural gas bridge is of limited direct emissions-reducing value, since that bridge must be short.” Yet Page et al. [77] assessed the global potential of CCS and concluded that it is “not presently a near-term measure for mitigating greenhouse gas emissions … In light of the tension between the current status of CCS and the need for rapid and deep emissions contractions … the value of further investment in CCS must be seriously questioned.” Moreover, Nordhaus and Pitlick [75] calculated that large-scale CCS would require a pipeline network comparable in size to natural gas infrastructure, making it prohibitively expensive; one follow-up assessment estimated that $58 trillion could be needed to establish this network in the United States alone [95].

4.2. Environmental degradation

Shale gas development can contribute to environmental degradation involving water, air, and the release of radionuclides, and the social degradation of public health; climate change; and the displacement of cleaner forms of energy supply. Because this subsection is the longest of any in the study (the extent of environmental degradation is the most hotly contested part of the fracking debate), it has been subdivided into three categories: pollution and public health, climate change, and displacement and social opposition.

4.2.1. Pollution and public health

The most extensively documented form of degradation relates to water availability and quality. As mentioned earlier, the drilling and operation of shale gas wells requires substantial quantities of water. As Table 6 summarizes, most sites in the United States need between 2.7 and 3.9 million gallons of water per well—or roughly 10–15 million liters of water. To catalyze the fracking process, drillers will add as many as a dozen chemicals, such as biocides, constituting 2 or 3 percent of the total volume of fracking fluid, and the fluid will invariably attract naturally occurring chemicals and salts from deep brines [52]. Howarth and Ingraffea [38] calculate that roughly 200,000 l of acids, biocides, scale inhibitors, friction reducers and surfactants are pumped under high pressure into each typical well.

This sheer water intensity of fracking has two implications. First, it is difficult to produce shale gas where water is scarce—something that matters given projections of water stress. Most of the world's water sources are already under stress, with one assessment calculating that global groundwater needs are 3.5 times in excess of the actual area of aquifers, and warning that 1.7 billion people live in areas "where groundwater resources and/or groundwater-dependent ecosystems are under threat" [31]. Modeling work undertaken by the United Nations Environment Program has revealed a series of water stress "hotspots" [1]. As Fig. 8 shows, areas shaded in black—including most of India and Northern China—will be under "severe water stress" by 2030. That is, the ratio of expected water withdrawals increases between 1995 and 2030 to a degree where it becomes impossible, by a wide margin, to adequately meet demand for water. Yet, as [32] emphasize, "in regions where local, natural water sources are scarce or dedicated to other uses, the limited availability of water may be a significant impediment to gas resource development."

Second, apart from water availability is the potential for shale gas production to lower water quality. Shale gas production generates waste from drilling muds, flowback, and produced brines that all require proper treatment and disposal [36]. Some of these quantities can be quite large, with 10–35 percent of initial chemical-water injections returning to the surface as flowback before production begins. However, one study notes that:

> *Improper well casing, lax on-site wastewater storage practices and perhaps even the hydraulic fracturing process itself can allow natural gas constituents to migrate into and permanently contaminate underground aquifers and private wells. The dumping of flowback waters into streams and onto roads contaminate surface waters and improperly treated fracking wastewater at sewage treatment plants damage streams and drinking water supplies, putting human and ecological health at risk [3].*

Additionally, faulty cementing has been known to contaminate water sources when gas wells fail [70]. In Pavillion, Wyoming, for instance, the U.S. Environmental Protection Agency has recorded toxic or carcinogenic compounds added to fracking fluid found in drinking wells adjacent to drill pads [20]. In a study of 68 private drinking water wells in northeastern Pennsylvania and New York, methane contamination rose sharply with proximity to natural gas drilling and fracking sites [76], though these results have been challenged by Molofsky et al. [69]. Furthermore, in these two states some of the fracking waste had been treated in municipal sewage plants that were not designed to handle toxic substances. Consequently, tributaries of the Ohio River have been contaminated with barium, strontium and bromides from municipal wastewater treatment plants [38]. Another survey of the five states that systematically report incidents at wells where fracking occurs estimated that 2% of them may end up contaminating groundwater with fracking fluids [6].

Future risks may be even more significant, with Myers [72] arguing that "there is substantial geologic evidence" that fracking will accelerate—that is, will greatly shorten—the transportation times that most toxic contaminants cycle towards the surface, reducing what would ordinarily take tens of thousands of years to hundreds of years (though their results have been critiqued by Saiers and Barth [87]). The scientific community would likely know more about the relationship between fracking and water quality but has limited data since shale gas production is currently exempted from the U.S. Safe Water Drinking Act, making it difficult to systematically monitor possible groundwater contamination [50,102,51].

A second environmental concern is air pollution. Most shale gas wells rely on diesel powered pumps to inject and manage water, leading to dangerous levels of volatile hydrocarbons (such as benzene, toluene, and formaldehyde), ground-level ozone, and particulate pollution associated with drills, compressors, and other machinery. In addition, shale gas development necessitates thousands of trucks delivering water to well sites as well as venting techniques to maximize production efficiency [3]. In Texas, benzene concentrations over the Barnett shale area have exceeded acute toxicity standards to the point where they pose a risk of cancer from chronic exposure [38]. Colorado has experienced increased ozone-forming pollutants along its Front Range with measured ozone precursor emissions "twice the amount that government regulators… calculated should exist" [36], and Wyoming has seen air pollution become a "a major challenge" to shale gas production there [51]. The Pennsylvania Department of

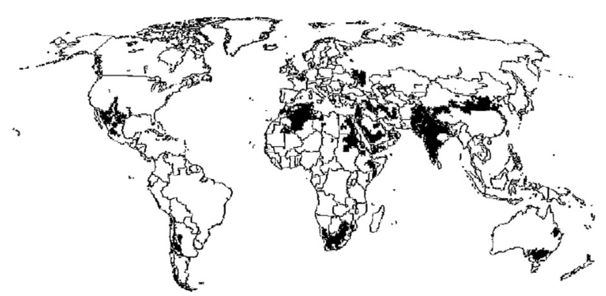

Fig. 8. Global water stress and water scarcity.
Source: Alcamo and Henrichs [1].

Table 6
Water needs per-well from shale gas plays in the United States.
Source: Sakmar [89].

Shale Gas Play	Volume of Drilling Water per Well		Volume of Fracturing Water per Well		Total	
	Gallons	Liters	Gallons	Liters	Gallons	Liters
Barnett Shale	400,000	1,514,164	2,300,000	8,706,443	2,700,000	10,220,607
Fayetteville Shale	60,000	227,125	2,900,000	10,977,689	3,060,000	11,583,355
Haynesville Shale	1,000,000	3,785,410	2,700,000	10,220,607	3,700,000	14,006,017
Marcellus Shale	80,000	302,833	3,800,000	14,384,558	3,880,000	14,687,391

Environmental Protection has recorded levels of nitrogen oxides and volatile organic compounds "well above" EPA standards near shale gas producing wells [89].

What also matters is whether one considers only a well or a collection of wells and sites. A study of air emissions from natural gas drilling in Pennsylvania illustrated the gap between macro- and micro-level experiences. It found that while the total emissions of a single well were less than that of a single coal-fired power plant, in areas where drilling was concentrated emissions were "20–40 times higher" than what regulations permitted for a single minor source [28].

A third environmental concern is radiation from the release of naturally occurring radionuclides that surface during the production process. New York's Department of Environmental Conservation reports that thirteen samples of wastewater from Marcellus Shale gas extraction contained levels of radium-226 as high as 267 times the safe disposal limit and thousands of times the limit safe for people to drink; the New York Department of Health also analyzed three Marcellus Shale production brine samples and found elevated gross alpha radiation, gross beta radiation, and radium-226 in the production brine [51]. Resnikoff [82] calculated radon levels 70 times higher than the average from the Marcellus gas field and determined that some shale gas deposits contain as much as 30 times the radiation that located in the normal background. Other studies of the Haynesville Shale (in Texas) and the Marcellus Shale (in Pennsylvania) have recorded high levels of radon, radium, and other radioactive substances [55]. Duke University researchers injected isotopic tracers into several shale gas basins across the United States—including the Utica, Marcellus, and Fayetteville plays—and confirmed "high levels" of salinity, toxic elements such as barium, and radioactivity [108]. In Sweden, the uranium content of shales exceeds 80 ppm, meaning it requires special permits from the Swedish Radiation Safety Authority [21]. Such findings connecting radioactivity to shale gas production have been confirmed by other studies documenting hazardous releases of radium and strontium contamination from hydraulic fracturing fluid and/or produced brines containing toxic substances during drilling, transport, and disposal [13,86,22].

The issue is not only that contaminated rock cuttings and cores create potential occupational exposure to radioactivity, but also that radioactive pollutants could persist in the produced gas traveling through pipelines and entering households. As Hamilton College Professor James R. Ring has noted:

> *The radon and natural gas coming from the shale mix together and travel together as the gas is piped to customers. This is a serious health hazard, as radon––being a gas—is breathed into the lungs and lodges there to decay, doing damage to the lung's tissue and eventually leading to lung cancer (Quoted in* [101]*).*

Radon has particularly egregious health implications given that it is an acute carcinogen second only to smoking in the United Kingdom as the leading cause of lung cancer [33].

Collectively, these negative impacts related to water, air, and radioactivity have convinced some analysts that fracking has severe health risks for those working in the industry and living near shale gas sites. One assessment, compiled from Pennsylvania Department of Environmental Protection and the Susquehanna River Basin Commission Material Safety Data Sheets for 41 products used in shale gas operations, analyzed fracking chemicals and concluded that 73% of the products "had between 6 and 14 different adverse health effects including skin, eye, and sensory organ damage; respiratory distress including asthma; gastrointestinal and liver disease; brain and nervous system harms; cancers; and negative reproductive effects" [19]. Investigators from the Colorado School of Public Health analyzed shale gas production in Garfield County and found that many community members residing within 600 feet of well pads experienced chemical exposures, accidents resulting from industry operations, and psychological impacts such as depression, anxiety, and stress [89]. In Dish, Texas blood and urine samples taken from residents living near Barnett Shale gas wells revealed that 65% of households tested had toluene in their systems and another 53% had detectable levels of xylene [80]. In Pavilion, Wyoming, the EPA documented that many drinking water wells were contaminated by toxics often used in hydraulic fracturing fluids, and suggested that they may be linked to abnormal rates of miscarriages, rare cancers, and central nervous system disorders including seizures [80]. As one medical journal concluded, "The potential negative impact of natural gas well drilling on the environment and health of thousands of families and children … is disconcerting" [57]. Some evidence even suggests that fracking is harmful to non-human life as well. University researchers in Pennsylvania have documented that milk production decreased by 19 percent in Pennsylvanian counties with 150 or more Marcellus Shale wells compared to a 1.2 percent decrease in counties with no wells [30].

4.2.2. *Climate change*

Another fiercely debated environmental issue is climate change. The leaks described in the technological sophistication subsection mean more methane is going into the atmosphere than previously expected. The World Bank estimates that the annual volume of associated natural gas being flared and vented—from conventional and unconventional sources—is about 110 billion cubic meters, enough to meet the annual natural gas consumption of Germany and France [46]. Methane is a greenhouse gas 21–23 times more potent than carbon dioxide on a 100 year timeframe, and its half-life is only 12 years, meaning its instantaneous impact is much larger on the climate system. Methane is already the second-largest contributor to anthropogenic greenhouse gas emissions after carbon dioxide, accounting for 16 percent of the total on a CO_2 equivalent basis [45]. Cornell scientist Robert W. Howarth and his colleagues expect that this makes methane emissions from shale gas between 130 and 200 percent worse than conventional natural gas. Put another way, Howarth and Ingraffea [38] argue that over 20 years, shale gas is likely to have a greater greenhouse effect than conventional gas and other fossil fuels—figures reflected in Fig. 9.

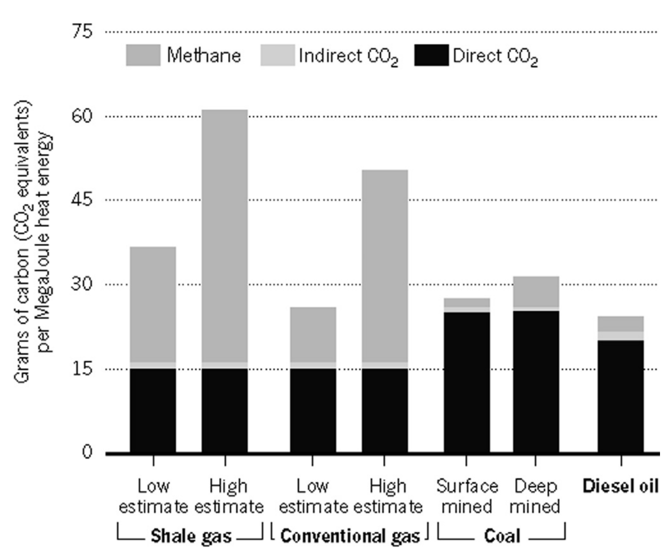

Fig. 9. Greenhouse gas emissions from shale gas, conventional gas and coal. *Source*: Howarth and Ingraffea [38].

Though Howarth's figures have been disputed,[1] a few recent studies seem to confirm his basic findings. Brandt et al. [10] analyzed more than 200 earlier studies of natural gas emissions spanning 20 years and confirmed that methane leakage rates are considerably higher than official estimates. Alvarez et al. [2] projected that current leakage rates from natural gas production and delivery mean that a switch from petroleum fueled vehicles to natural gas powered vehicles would have a net *negative* impact on climate change, given that at least 3.2 percent of methane is currently leaking from natural gas infrastructure. The authors warn that leakage rates for shale gas are probably worse. The International Energy Agency [44] reports that "unconventional gas has higher production-related greenhouse-gas emissions than conventional gas" and that "releases of methane, wherever they occur in the gas supply chain, are particularly damaging, given its potency as a greenhouse gas." Hultman et al. [42] reached a more moderate, yet still troubling conclusion, and found that for electricity generation shale gas was 11 percent worse (from an emissions standpoint) than ordinary gas but not worse than coal. Their study may be more fine-tuned given that it distinguishes between end uses such as heating and electricity, that it uses a greater variety of global warming potentials, and that it accounts for shale gas operators learning from past failures and developing more efficient technology.

4.2.3. *Displacement and social opposition*

A final social and environmental aspect to shale gas production concerns its ability to displace arguably cleaner forms of energy—such as renewable electricity or nuclear power—and the fact that it has been prone to social opposition across the world.

In terms of displacement, shale gas production has begun (perhaps oddly) to lead to more oil and coal use and less renewable electricity and nuclear power. The drop in the price of natural gas motivated by shale gas, and summarized above, has driven America's drillers to hunt for oil instead, and to use fracking technology to liberate liquid fuel rather than gaseous fuel. Indeed, the application of fracking to "tight oil" reserves in the Permian Basin and Eagle Ford Shale in Texas, the Bakken formation of North Dakota and the Mississippian Lime between Oklahoma and Kansas has enabled the United States to overtake Russia and Saudi Arabia to become the world's biggest producer of crude oil in 2013 [24]. Due to analogous concerns over cheap natural gas prices, other companies have shifted away from drilling for dry gas and instead are focusing on plays that provide natural gas liquids [60]. And, although coal use in the United States has declined, the foreign export market has more than made up for the loss, meaning more coal is now being combusted in Europe and Asia [78].

Cheap natural gas has also stunted the growth of renewable sources of electricity such as wind and solar and nuclear power. Before the fracking boom, wind energy was expected to overtake natural gas, with wind power making up 42 percent of electric generating capacity additions in 2009, and at the end of 2010, planners anticipated another 258 GW of wind power capacity—more than six times existing installed capacity—to be installed in coming years [112]. Yet the most recent dips in the price of natural gas mean it will now "take over" and account for the largest capacity additions, with the EIA [107] anticipating that natural gas-fired plants will account for 63 percent of new electricity capacity from 2012 to 2040 in the United States compared with 31 percent for renewables, 3 percent for coal, and 3 percent for nuclear energy—see Fig. 10. As researchers at MIT noted, "as would be expected, the cheaper gas serves to reduce the rate of market penetration of renewable generation" [47]. Howarth and Ingraffea [38] state that "shale gas competes for investment with green energy technologies, slowing their development and distracting politicians and the public from developing a long-term sustainable energy policy." Economists from Resources for the Future have calculated that shale gas development means that "some coal is displaced from the energy mix, but so are zero-emission nuclear energy and renewables. As a result, both energy consumption and carbon dioxide emissions increase slightly" [52]. And Parenteau and Barnes [78] argue that "accommodating a large-scale shift toward natural gas assumes an investment of billions of dollars' worth of wells, pipelines, storage, and additional midstream infrastructure investments" which "will impede renewables unless steps are taken to prevent it."

Consequently, shale gas could meaningfully tradeoff with renewables and cleaner forms of electricity supply [58], rather than accelerate their promotion, and "lock" economies into fossil-fueled infrastructure for years to come. Myhrvold and Caldeira [73] assessed future energy portfolios and determined that energy efficiency, wind, solar, nuclear power, and possibly carbon capture and storage appear to be able to achieve substantial climate benefits in the second half of this century, but that natural gas cannot, because of the high global warming potential of methane. As the authors conclude, "technologies that offer only modest reductions in emissions, such as natural gas … cannot yield substantial temperature reductions this century." Energy governance scholar Westphal [111] writes that "unconventional fuels are no solution for global energy problems. At best they offer a viable bridge for conversion of the energy system, at worst they perpetuate existing use paths."

Because of these negative environmental attributes spanning air, water, public health, and climate, it may come as no surprise that fracking has provoked social opposition and protest in many parts of the world. The Economist [23] conducted a global public attitudes survey of fracking and found that the public was almost

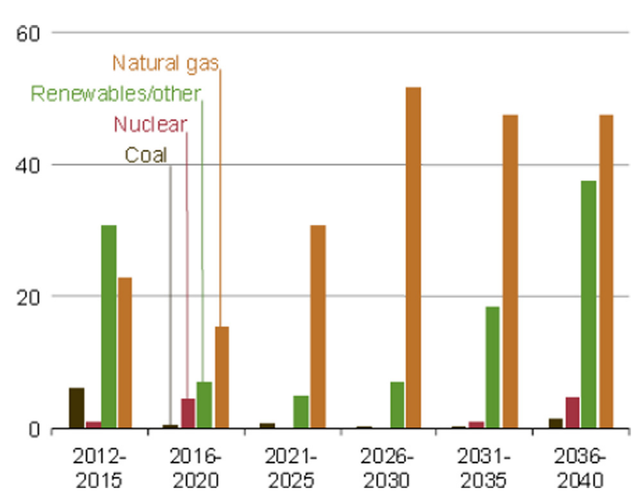

Fig. 10. Electricity generation capacity additions by fuel type, 2012–2040 (gigawatts).
Source: U.S. EIA [107].

[1] The industry and other experts have aggressively challenged Howarth's figures. One leading critic is Cathles [12], Professor of Earth and Atmospheric Studies at Cornell, who argues that Howarth's study is flawed in several respects: (1) that it "significantly overestimate[s] the fugitive emissions associated with unconventional gas extraction;" (2) that it "undervalue[s] the contribution of 'green tech-nologies' to reducing those emissions to a level approaching that of conventional gas;" (3) that it incorrectly bases the "comparison between gas and coal on heat rather than electricity generation;" and (4) that it "assumes a time interval over which to compute the relative climate impact of gas compared to coal that does not capture the contrast between the long residence time of CO2 and the short residence time of methane in the atmosphere." Howarth and his colleagues quickly issued a rebuttal in [39]. Thanks to Parenteau and Barnes [78] for pointing this out to the author.

evenly split 51 percent against and 49 percent for it. As of March 2013, four European countries—Bulgaria, the Czech Republic, France, and the Netherlands—had outright banned fracking. In Texas, signs saying "Get the Frack Out of Here" and "Protect Our Kids/No Drilling" have appeared in Dallas and a few communities have declared temporary moratoriums [29]. In Philadelphia, Pennsylvania, a "Shale Outrage" rally took place and boasted more than a thousand attendees [40]. In Albany, New York, residents successfully convinced the state government to pass a moratorium. Indeed, political scientist Rahm [80] expects such disagreements to intensify as "pro-drilling and anti-drilling groups will continue to use the courts and the political or administrative powers at their disposal to win their goals".

Now, to be fair, social opposition is a bit of chicken-or-egg problem [17]. Are people opposing because they do not like shale gas or are they opposing because they have been scared by the newspaper articles, blogs, reports, and non-peer reviewed studies, some of which the author quotes? Also, interestingly, social opposition appears to be lessened in regions where people are used to industrial activity and, especially, where landowners are also owners of the mineral rights and increased their incomes multifold.

4.3. Earthquakes and seismicity

Hydrofracking and shale gas production can contribute to increased seismicity and earthquakes, though it must be emphasized that these are more on the scale of "annoyances" than major catastrophic earthquakes that wreck entire cities. Still, the U.S. Geological Survey published a study that documented a sevenfold increase in seismic activity in central US since 2008 that is at least partially attributed to increased shale gas production [25]. Furthermore, the National Research Council [74] has published preliminary findings that the injection and withdrawal of fracking fluid can cause increased seismicity, though it does note relatively "few events" compared to the large number of disposal wells in operation.

However, other elements of the production process—notably deep disposal of fracking's wastewater—have been shown repeatedly to cause "disturbingly strong earthquakes" registering 4 or 5 on the Richter scale which are "rattling the local populace, shutting down clean energy projects, and prompting a flurry of new regulations" [53]. According to Kerr [53], the Arkansas Geological Survey has documented a cluster of earthquakes near Greenbrier correlated with deep disposal of fracking wastes. The Guy-Greenbrier area had had only one quake of magnitude 2.5 or greater in 2007 and two in 2008 when fracking was only beginning, but there were 10 in 2009, the first year of deep disposal, and 54 in 2010. Researchers discovered that fracking water had been injected into an aquifer 3 km down, where it increased the pressure of groundwater in the rock's pores and fractures, triggering a previously unknown buried fault that germinated the quakes. Indeed, injection of fracking wastewater under the Dallas/Fort Worth International Airport in Texas caused more than 180 earthquakes ranging up to magnitude 3.3 in 2008 and 2009, which suddenly stopped once the injections ceased [53].

4.4. Unclear profitability

A final concern, perhaps counter intuitive given the scale of investment ongoing into shale production, is that when all costs are accounted for hydrofracking may not be profitable. Part of the uncertainty relates to the difficulty in measuring proven reserves; another relates to the low profit margins of existing fields; yet another the economic impacts on traditional producers of natural gas; a final part concerns the economic cost of externalities associated with shale gas production.

Table 7 shows three prominent estimates of shale gas reserves around the world—and it notes that figures reflecting total reserves differ by 60 percent and that some estimates of regional deserves differ by 400 and 500 percent. Signifying how problematic estimating reserves can be, in 2011 the U.S. Geological Survey released a new estimate of the amount of gas in the Marcellus shale formation (the largest shale-gas formation in the United States), and determined that the Department of Energy has overestimated the resource by some five-fold [14]. Researchers at MIT similarly compiled seven years of natural gas estimates from groups such as the National Petroleum Council, the Potential Gas Committee, and the U.S. Energy Information Administration and found that estimates varied from a low of 1437 tcf to a high of 2319 tcf—a difference of 62 percent illustrated by Fig. 11 [68].

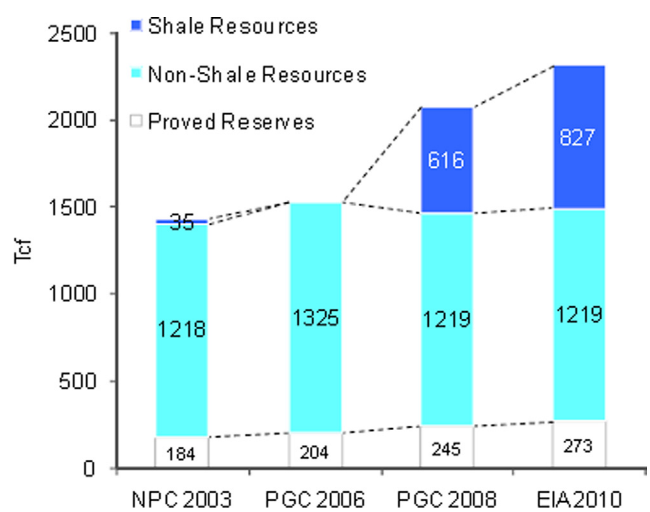

Fig. 11. Estimates of U.S. natural gas resources.
Source: MITEI [68].

Table 7
Global estimates of technically recoverable shale gas reserves.
Source: Rogner [84], Boyer et al. [9], U.S. EIA [106], ICF International [43].

Region	1997 Rogner Study (Tcf)	2011 EIA Study (tcf)	2012 ICF Study (mean tcf)	% Dif from Lowest to Highest
North America	3.842	7.140	1.863	383.3
South America	2.117	4.569		215.8
Europe	549	2.587	520	497.5
Africa	1.548	3.962		39.1
Asia	3.528	5.661	1.100	514.6
Australia	2.313	1.381		59.7
Other	2.215			
Total	16.112	25.300		63.7

What accounts for this uncertainty? One complicating factor is attempting to determine the proper peak for most shale gas fields, which can range from less than 10 years to more than 50 years under certain scenarios. Another is the lack of experience with the resource. As one energy geologist explained, "at this stage of the game, we have very little experience with shale gas … Predictions of well performance over 15–20 years are based on 6–24 months of experience" [52]. Yet another is possible bias in forecasting. Kinnaman [56] conducted his own meta-survey of shale gas estimates and found that "reports sponsored by the gas extraction industry and issued with academic institution affiliation" tended to habitually overstate reserves and potential revenues to inflate expectations.

Confounding the potential profitability of shale gas is the quickness with which wells are depleted and low ultimate recovery rates [85]. While a conventional well can produce gas for upwards of 40 years, shale gas fractures peak within a matter of 30–40 months—as the production profiles in Fig. 12 indicate. Most shale gas wells in fact exhibit decline rates of 60–80 percent in their first year of operation, though this slows to about 10 percent per year afterwards; in effect this means that shale producers exchange a reduction in exploration risk for an increase in production risk [47].

Due to these rapid rates of depletion, in some sites, production costs in plays exceed current gas prices, and maintaining production is beginning to require even greater amounts of capital. Hughes [41], a geoscientist and a fellow at the Post Carbon Institute, analyzed 30 shale gas plays with 65,000 shale wells in the United States, and noted that five fields produced 80 percent of the gas and that typical well output dropped 80–95 percent in its first three years. This required producers to tap as many fields as possible to maintain stable output. In other words, new wells must constantly be drilled to maintain constant supply. In the Haynesville play, Hughes estimates that 800 wells, or one-third of those active in 2012, had to be added each year to keep shale-gas output at 2012 levels. With capital costs of around $9 million per well, drilling to keep production flat costs some $7 billion a year, excluding the secondary costs of leasing, infrastructure and interest. Nationwide, this means $42 billion is needed to offset declines in production, yet in 2012 shale gas generated only $33 billion in revenues. As Hughes concluded, "to break even in shale-gas plays without liquids production, gas prices would have to rise. Shale gas thus requires large amounts of capital from industry to maintain production. Governments and industry must recognize that shale gas and oil are not cheap or inexhaustible, [and that] 70% of US shale gas comes from fields that are either flat or in decline" [41].

An interdisciplinary team from MIT [47] confirmed such dire findings when they estimated that most shale gas wells in the United States failed to make an expected 10 percent rate of return and that, most worryingly, "companies are not making money at 2011 gas prices (around $4 per Mcf), and that evidence of overreaching today should dampen confidence in the future of this resource." Looking to the future, the costs of shale gas production could rise dramatically after drillers have depleted all of the "sweet spots" where geology has enabled ease of extraction [52].

A third negative economic implication of shale gas production is its impact on traditional gas producers. While it has been a boon for US producers it has been a bane for traditional liquefied natural gas (LNG) exporters. As Deutch [18] explains:

> *For years, major natural gas holders—such as Australia, Bolivia, Iran, Russia, Saudi Arabia, and the United States—anticipated a future of high, oil-linked gas prices. They invested in expensive LNG liquefaction facilities and pipeline projects. But now, these countries are facing a reduction of the value of the resource in the ground. A dramatic increase in the global availability of unconventional gas and lower natural gas prices could put these and other planned investments under water.*

The impact of plentiful, cheap shale gas is already having significant repercussions on traditional exporters of LNG. As Fig. 13 reveals, the rise in shale gas production has seen conventional production of LNG stagnate or decline in all but 3 major countries [23]. In addition, in 2013 analysts determined that North American output of low-priced shale gas had placed $160 billion worth of natural gas investments by major companies such as Chevron and ExxonMobil "at risk" in Australia [54].

Finally, if one attaches an economic cost to all of the externalities discussed above, shale gas no longer becomes "cheap." It only appears artificially affordable when such externalities are excluded from its price tag. The *American Journal of Public Health* has summarized some of the unpriced negative externalities from shale gas as follows:

> *Toxic mud and fluid byproducts from the drilling and fracking as well as spills of oil and gas wastes are not uncommon. Of the more than 8600 abandoned wells in Pennsylvania in 2009 alone, taxpayers paid to plug 259 because of leaking natural gas, oil and acid mine drainage into the groundwater, surface water, and*

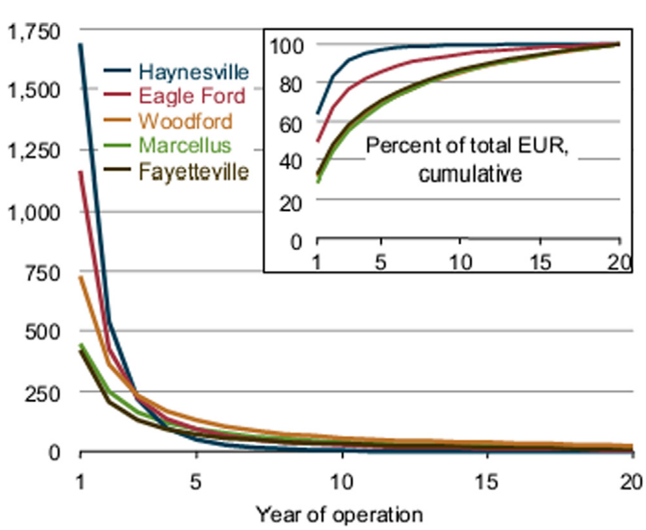

Fig. 12. Average production profiles for shale gas wells in major U.S. shale plays by years of operation (Mcf/year).
Source: U.S. EIA [107].

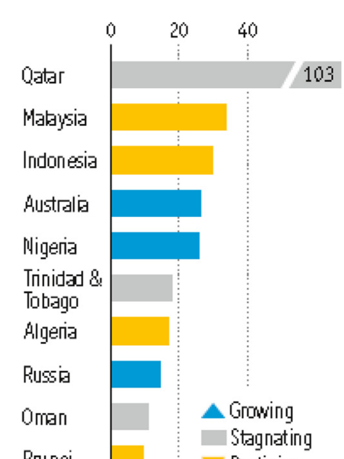

Fig. 13. Trends in global LNG production (billion cubic meters), 2012.
Source: Economist [23].

air. Postmineral extraction cleanup costs are substantial, including restoration of damaged or contaminated streams and soil, improper handling of wastewater disposal, and improper disposal of radioactive material and hazardous waste. Soil contamination also has not been addressed fully. Drilling sludge (a mixture that includes drilling mud and rock cuttings containing hydrocarbons, radioactive material, and heavy metals) is brought to the surface during the drilling phase. Flowback waste fluids, a byproduct of the fracking phase, must be disposed of safely because they can potentially contaminate air and soil. Radioactive hazardous waste needs to be taken to special disposal sites. However, clandestine dumping is widely suspected, thus further jeopardizing both soil and watersheds [27].

When these externalities become factored into shale gas production costs, various peer-reviewed studies suggest that natural gas becomes far more expensive than most forms of renewable electricity including wind energy, geothermal, hydroelectricity, bio-electricity, and some forms of solar energy [62,63,99,100].

5. Conclusions and implications

What are we to make of these conflicting aspects of shale gas production—that it brings the promise of substantial benefits only at a considerable cost? Do the cons outweigh the pros? Should we completely abandon shale gas and fracking altogether? No, not necessarily. Instead, this section of the study presents four more nuanced conclusions.

First, shale gas production brings measurable benefits as well as discernible costs summarized by Table 8. Tangible benefits include potentially massive available reserves, a rapid depression of natural gas (and thus energy and commodity) prices that have already begun to occur, less damage to the environment than coal and oil (under certain assumptions), and robust economic growth, employment, and development. Tangible costs include dependence on complex technical systems prone to leakage and accidents, severe damage to social communities, the environment, and the atmosphere when things go wrong, a heightened risk of earthquakes, and an unclear profit margin when externalities are taken into consideration. Sticking with the analogy from the introduction, it will invariably lead to more "frack burgers" as well as more homes like the one belonging to David Headley. Shale gas production, Melo-Martín et al. [67, p. 1115] highlight, "pits potential gains in economics, employment, energy independence, and national security against potential harms to the environment, the climate, and public health".

Further obfuscating matters, though, these costs and benefits are not distributed evenly. Some benefits and risks, such as economic development or water contamination, occur now, while others, such as climate change or declining production and profit margins, will occur in the future. They also occur at different scales: the land, air, and human health impacts associated with fracking tend to be localized, whereas the systemic forcings of climate change are globalized. And they occur to different actors: landowners and producers benefit, conventional LNG exporters and those living adjacent to wells may suffer. In this way, shale gas production is really about picking your poison, and deciding which series of risks are acceptable but never eliminating risk itself.

Second, because of this complicated and contested nature of fracking—that it is both boon and bane to different sets of stakeholders—the fracking "debate" may be irresolvable, since both "sides" can point to an array of data supporting their claims, and simply ignore countervailing data that they do not like. In this way, fracking is a reminder that energy systems involve not only technologies and policies but also politics and values; and current production techniques all but guarantee inevitable conflict between companies and environmentalists, those leasing their land upstream and those suffering from pollution downstream, importers and exporters, and advocates of "clean" fossil fuels (such as CCS and natural gas) versus advocates of nuclear power and renewable electricity. And so shale gas will likely remain divisive and polemical for decades to come.

Third, because of its contested complexity, we can expect shale gas to have different development trajectories around the world. Put another way, the shale gas boom, if there is one, will neither be uniform nor entirely predictable. Because every fracked site is unique, the particular array of costs and benefits will play out differently at each location, shaped by a multitude of factors including geology and the availability of injection disposal wells, type and location of technology, corporate governance, regulation related to waste discharges and transportation, natural gas prices, and social demographics. We already see some of this divergence between North America, which has largely embraced fracking, and European countries, which are more cautious. Stevens [98], Bazilian et al. [5], Selley [91], and Asche et al. [4] have argued that its comparative population density (which puts more communities around fracking sites), stronger environmental restrictions and moratoriums, and lack of easy access to pipeline distribution

Table 8
Summary of shale gas pros and cons.

Pro	Con
5760 trillion cubic feet of recoverable gas potentially available and fortuitously situated close to major energy consumers such as China, India, and the United States and worth trillions of dollars	Extraction requires site specific, complex, capital intensive technology prone to leakage, accidents, and earthquakes, and may be dependent on carbon capture and storage to achieve long-lasting carbon gains
Affordable production prices 50–66 percent cheaper than ordinary gas that are then passed onto consumers and industries	Profit margins are unclear and may be negative due to the rapid depletion of wells and the inclusion of all social and environmental costs
The ability to "break" longstanding monopolies of natural gas supply (e.g. Russia or Venezuela)	Serious economic risks to conventional natural gas producers such as Qatar, Australia, Trinidad and Tobago, and Oman
Use in the electricity sector tends to lower overall greenhouse gas emissions intensity and lead to the retirement of coal-fired power plants	Under certain assumptions can have a higher footprint than coal and other fossil fuels and a more immediate impact on the climate due to the potency of methane
Can begin to substitute for petroleum and oil in the transportation sector, lowering the environmental impact of that sector	Has an equal propensity to "lock-in" investments in fossil fueled infrastructure and displace energy efficiency, renewable electricity, and nuclear power
Creates thousands of jobs, millions of dollars of tax revenues, and billions of dollars of investment in each region that adopts widespread fracking	Is water intensive and therefore may not be possible in areas prone to water stress and can contribute to the serious deterioration of water quality and the release of radionuclides and local air pollution, threatening public health as well
Strongly endorsed by landowners standing to profit from shale gas leases, energy companies wishing to develop resources, and energy-independence-minded political leaders	Strongly opposed by community members without access to reserves, environmental groups and nongovernmental organizations, and renewable energy and nuclear power advocates

networks, among other factors, make it unlikely that Europe will adopt shale gas within the next decade. As Johnson and Boersma [50] succinctly put it, “no European country has a history of commercial development of shale gas, and it is still far from certain that a single cubic meter of gas will be commercially produced.” By contrast, the extensive network of existing pipelines, well-defined and analyzed nature of reserves, long history of oil and gas production, public nature of mineral rights and shared royalty schemes, and dreams of striking it rich as a “wildcatter” have created an environment in the United States highly amenable to fracking [92,88]. The future will likely hold even more diverse and divergent shale gas development pathways than these around the world.

Fourth is that the efficacy and utility of shale gas production and fracking depends on sound governance principles. That is, it can work with proper safeguards in place, when it is comprehensively regulated and enforced in a fully transparent manner with robust measuring and monitoring of environmental impacts and meaningful engagement with local communities. As the International Energy Agency [44] has emphasized, leaks from wells into aquifers can be prevented by high standards of well design, construction and integrity testing. Thorough assessment and monitoring of water requirements can engender informed and stringent water handling and disposal techniques. The elimination of venting can reduce greenhouse gas emissions. Done in this manner, the scale and scope of shale gas's advantages rise, while its disadvantages recede [97].

However, when the opposite occurs, the disadvantages of shale gas tend to trump its advantages. When production is exempt from drinking water and hazardous waste regulations (as they are in the United States), scientists face difficulty determining the extent of environmental degradation and municipal sewage plants unknowingly exacerbate pollution due to improper treatment [71]. When surface water withdrawals are poorly managed, fracking can decrease water quality in streams, leading to a reduction in quality and competition with other water needs. When construction and operation of drilling pads are poorly regulated, spills and leaks can occur, further contaminating groundwater, airsheds, and the global climate. Worse, uncertainty itself can give rise to public opposition and, in extreme cases, moratoriums.

In this way, successful management of shale gas is not a given; whether it leads to degraded communities and impoverished environmental wastelands or vibrant energy-independent societies is a matter of choice. As Wang et al. [110, p. 1] recently concluded, “Enforcing stronger regulations [is] necessary to minimize risk to the environment and on human health.” The benefits of shale gas production are uncertain, conditional on the “right” mix of technological systems, operating procedures, government regulations, and corporate values at each locality. All is a matter of polarity: one community may perceive shale gas as an alluring opportunity while another sees it as a treacherous threat.

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References

[1] Alcamo J, Henrichs T. Critical regions; a model-based estimation of world water resources sensitive to global changes. Aquat Sci 2002;64:3523621.
[2] Alvarez RA, Pacala SW, Winebrake JJ, Chameides WL, Hamburg SP. Greater focus needed on methane leakage from natural gas infrastructure. Proc Natl Acad Sci 2012;109:6435–40.
[3] Argetsinger Beren. The marcellus shale: bridge to a clean energy future or bridge to nowhere? Environmental, energy and climate policy considerations for shale gas development in New York State Pace Environ Law Rev 2012;29:321–43.
[4] Asche Frank, Oglend Atle, Osmundsen Petter. Gas versus oil prices the impact of shale gas. Energy Policy 2012;47:117–24.
[5] Bazilian Morgan, Pedersen Ascha, Baranes Edmond. Considering shale gas in Europe. Eur Energy J 2013;3(1):36–63.
[6] Bishop RE. Chemical and biological risk assessment for natural gas extraction in New York. Oneonta, NY: State University of New York College at Oneonta; 2011 (Cooperstown, NY: Sustainable Otsego).
[7] Bocora Jan. Global prospects for the development of unconventional gas. Procedia – Soc Behav Sci 2012;65:436–42.
[8] Boote David N, Beile Penny. Scholars before researchers: on the centrality of the dissertation literature review in research preparation. Educ Res 2005;34(6):3–15.
[9] Boyer Chuck, Clark Bill, Jochen Valerie, Lewis Rick, Miller Camron K. Shale gas: a global resource oilfield review, vol. 23(3); 2011. p. 28–39.
[10] Brandt AR, Heath GA, Kort EA, O'Sullivan F, Pétron G, et al. Methane leaks from North American natural gas systems. Science 2014;343(14):733–4.
[11] Burnham A, et al. Life-cycle greenhouse gas emissions of shale gas, natural gas, coal, and petroleum. Environ Sci Technol 2012;46(2):619–27.
[12] Cathles Lawrence M et al. A commentary on “The Greenhouse-Gas Footprint of Natural Gas in Shale Formations” by R.W. Howarth, R. Santoro, and Anthony Ingraffea, 113 Climatic Change 525; 2012.
[13] Chapman EC, Capo R, Stewart BW, Kirby C, Hammack RW, Schroeder K, et al. Geochemical and strontium isotope characterization of produced waters from Marcellus Shale natural gas extraction. Environ Sci Technol 2012;46:3545–53.
[14] Coleman JL, et al. Assessment of undiscovered oil and gas resources of the Devonian marcellus shale of the Appalachian Basin Province, 2011. US Geological Survey Fact Sheet; 2011. p. 2011–3092.
[15] Cooper Harris M. Scientific guidelines for conducting integrative research reviews. Rev Educ Res 1982;52(2):291–302.
[16] D'Agostino AL, Sovacool BK, Trott K, Ramos CR, Saleem S, Ong. Y. What's the state of energy studies research?: a content analysis of three leading journals from 1999–2008 Energy 2011;36(1):508–19.
[17] DeCicco JM. The “chicken or egg” problem writ large: why a hydrogen fuel cell focus is premature. In: Sperling D, Cannon J, editors. The hydrogen energy transition: moving toward the post-petroleum age in transportation. Burlington (MA): Academic Press; 2004 (Chapter 15).
[18] Deutch John. The good news about gas: the natural gas revolution and its consequences. Foreign Aff 2011:82–93.
[19] Diamanti-Kandarakis E, Bourguignon JP, Giudice LC, et al. Endocrine disrupting chemicals: an Endocrine Society scientific statement. Endocr Rev 2009;30(4):293–342.
[20] DiGiulio DC, Wilkin RT, Miller C, Oberly G. Draft: investigation of ground water contamination near Pavillion, Wyoming. Ada, OK: EPA, Office of Research and Development; 2011.
[21] DNV. Risk management of shale gas developments and operations. January 2013 DNV-RP-U301; 2013.
[22] Dresel P, Rose A. Chemistry and origin of oil and gas well brines in Western Pennsylvania. Pennsylvania Geological Survey: 4th series Open-File Report OFOG 10-01.0; 2010. p. 48.
[23] Economist. Special report: natural gas; 2012.
[24] Economist. Deep sigh of relief; 2013.
[25] Ellsworth W, Hickman S, Llenos A, McGarr A, Michael A, Rubinstein J. Are seismicity rate changes in the midcontinent natural or manmade? Seismol Res Lett 2012;83:403.
[26] Engelder Terry. Should fracking stop? Nature 2011;477:274–5.
[27] Finkel Madelon L, Law Adam. The rush to drill for natural gas: a public health cautionary tale. Am J Public Health 2011;101(5):784–5.
[28] Foster Peter. Now for the downside of fracking By Daily Telegraph; 2013.
[29] Galbraith Kate. Resistance to gas drilling rises on unlikely soil. The Texas Tribune; April 23, 2011.
[30] Garber, Lisa. 5 Fracking consequences you've never heard about. Natural Society/News Report; February 27, 2013.
[31] Tom Gleeson, Wada Yoshihide, Bierkens Marc FP, van Beek Ludovicus PH. Water balance of global aquifers revealed by groundwater footprint. Nature 2012;488:197–200.
[32] Gregory Kelvin B, Vidic Radisav D, Dzombak David A. Water management challenges associated with the production of shale gas by hydraulic fracturing. Elements 2011;7:181–6.
[33] Health Protection Agency (HPA). Report of an independent Advisory Group on Ionising Radiation: Docs RCE 11, HPA 2009.
[34] Hirschberg Stefan, Burgherr Peter, Spiekerman Gerard, Dones Roberto. Severe accidents in the energy sector: comparative perspective. J Hazard Mater 2004;111:57–65.
[35] Holzman David C. Methane found in well water near fracking sites. Environ Health Perspect 2011;119(7):A289.
[36] House Evan J. Fractured fairytales: the failed social license for unconventional oil and gas development. Wyo Law Rev 2013;13:6–67.
[37] Howarth RW, Santoro R, Ingraffea A. Methane and the greenhouse-gas footprint of natural gas from shale formations. Clim Change 2011;106:679–90.
[38] Howarth Robert W, Ingraffea Anthony. Should fracking stop? Yes Nature 2011;477:271–4.
[39] Howarth Robert W, et al. Venting and leaking of methane from shale gas development: response to Cathles et al. Clim Change 2012.

[40] Hoye, Sarah. Fracking' protesters say drilling jobs not worth environmental risks CNN; 2011.
[41] Hughes J David. A reality check on the shale revolution. Nature 2013;494:308.
[42] Hultman Nathan, Rebois Dylan, Scholten Michael, Ramig Christopher. The greenhouse impact of unconventional gas for electricity generation. Environ Res Lett 2011;6:044008 (9 p.).
[43] ICF International. International natural gas resource trends implications of new natural gas resources and the environmental impact in the U.S., Europe, India, and China; 2012.
[44] International Energy Agency. Golden rules for a golden age of gas. Paris: OECD; 2012.
[45] IPIECA. Natural gas as a climate change solution: breaking down the barriers to methane's expanding role; 2006.
[46] Ismail O Saheed, Umukoro G Ezaina. Global impact of gas flaring. Energy Power Eng 2012;4:290–302.
[47] Jacoby Henry D O'Sullivan Francis M. Sergey Paltsev. The influence of shale gas on U.S. energy and environmental policy: MIT Joint Program on the Science and Policy of Global Change Report No. 207; 2011.
[48] Jacoby HD, O'Sullivan FM, Paltsev S. The influence of shale gas on U.S. energy and environmental policy. Econ Energy Environ Policy 2012;1:37–51.
[49] Jenner Steffen, Lamadrid Alberto J. Shale gas vs. coal: policy implications from environmental impact comparisons of shale gas, conventional gas, and coal on air, water, and land in the United States. Energy Policy 2013;53:442–53.
[50] Johnson Corey, Boersma Tim. Energy (in)security in Poland the case of shale gas. Energy Policy 2013;53:389–99.
[51] Kargbo David M, Wilhelm Rong, Campbell David J. Natural gas plays in the marcellus shale: challenges and potential opportunities. Environ Sci Technol 2010;44:5679–84.
[52] Kerr Richard A. Natural gas from shale bursts onto the scene. Science 2010;328:1624–6.
[53] Kerr Richard A. Learning how to not make your own earthquakes. Science 2012;225:1436–7.
[54] Kelly Ross. U.S. shale boom threatens Australian gas projects. Wall Str J 2013.
[55] Kharaka YK, Thordsen JJ, Conaway CH, Thomas RB. The energy–water nexus: potential groundwater-quality degradation associated with production of shale gas. Procedia Earth Planet Sci 2013;7:417–22.
[56] Kinnaman Thomas C. The economic impact of shale gas extraction: a review of existing studies. Ecol Econ 2011;70:1243–9.
[57] Lauver Lori S. Environmental health advocacy: an overview of natural gas drilling in northeast Pennsylvania and implications for pediatric nursing. J Pediatr Nurs 2012;27:383–9.
[58] Lee April, Zinaman Owen, Logan Jeffrey, Bazilian Morgan, Arent Douglas, Newmark Robin L. Interactions, complementarities and tensions at the nexus of natural gas and renewable energy. Electr J 2012;25(10):38–48.
[59] Levi Michael. Climate consequences of natural gas as a bridge fuel. Clim Change 2013.
[60] Logan Jeffrey, Heath Garvin, Macknick Jordan, Paranhos Elizabeth, Boyd William, Carlson Ken. Natural gas and the transformation of the U.S. energy sector: electricity. Golden, CO: NREL/TP-6A50-55538; 2012.
[61] Maffly Brian. Uinta Basin gas leakage far worse than most believe; new study says up to 12 percent of basin's methane escapes. Salt Lake Trib 2013.
[62] McCubbin D, Sovacool BK. The hidden factors that make wind energy cheaper than natural gas in the United States. Electr J 2011;24(9):84–95.
[63] McCubbin D, Sovacool BK. Quantifying the health and environmental benefits of wind power to natural gas. Energy Policy 2013;53:429–41.
[64] McKie Robin. Fracking is the only way to achieve Obama climate change goals, says senior scientist. Guardian 2013.
[65] Medlock Kenneth Barry. Modeling the implications of expanded US shale gas production. Energy Strategy Rev 2012;1:33–41.
[66] Medlock Kenneth Barry, Jaffe AM, Hartley P, et al. Shale gas and US national security; 2011. Available online at: http://www.bakerinstitute.org/programs/energy-forum/publications/energy-studies/shale-gas-and-u.s.-national-security.
[67] Melo-Martín I, Hays J, Finkel ML. The role of ethics in shale gas policies. Sci Total Environ 2014;470–471:1114–9.
[68] MITEI [MIT Energy Initiative]. The future of natural gas: an interdisciplinary MIT study. Cambridge, MA; 2011 Available at: 〈http://web.mit.edu/mitei/research/studies/natural-gas-2011.shtm〉.
[69] Molofsky LJ, et al. Evaluation of methane sources in groundwater in northeastern Pennsylvania. Groundwater 2013;51(3):333–49.
[70] Mooney Chris. Energy: the truth about fracking. Sci Am 2011:80–5.
[71] Murrill Brandon J, Adam Vann. Hydraulic fracturing: chemical disclosure requirements congressional research service. 7–5700; 2012.
[72] Myers T. Potential contaminant pathways from hydraulically fractured shale to aquifers. Groundwater 2012;50(6):872–82.
[73] Myhrvold NP, Caldeira K. Greenhouse gases, climate change and the transition from coal to low-carbon electricity. Environ Res Lett 2012;7:014019.
[74] National Research Council. Induced seismicity potential in energy technologies (pre-publication). Washington, DC: National Academies Press; 2012.
[75] Nordhaus Robert R, Emily Pitlick. Carbon dioxide pipeline regulation. Energy Law J 2009;30(2009):85–102.
[76] Osborn SG, et al. Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. Proc Natl Acad Sci USA 2011;108(20):8172–6.
[77] Page SC, Williamson AG, Mason IG. Carbon capture and storage: fundamental thermodynamics and current technology. Energy Policy 2009;37(9):3314–24.
[78] Parenteau Patrick, Barnes Abigail. A bridge too far: building off-ramps on the shale gas superhighway. Idaho Law Review 2013;49:325–66.
[79] Rahm Brian G, Riha Susan J. Toward strategic management of shale gas development regional, collective impacts on water resources. Environ Sci Policy 2012;17:12–23.
[80] Rahm Dianne. Regulating hydraulic fracturing in shale gas plays: the case of Texas. Energy Policy 2011;39:2974–81.
[81] Reeder Laura C. Creating a legal framework for regulation of natural gas extraction from the marcellus shale formation. William Mary Environ Law Policy Rev 2010;34:999–1026.
[82] Resnikoff Marvin. Radon in natural gas from marcellus shale (Radioactive waste management associates, January); 2012.
[83] Ridley Matt. The shale gas shock: the global warming policy foundation GWPF report; 2011.
[84] Rogner HH. An assessment of world hydrocarbon resources. Victoria (BC): Institute for Integrated Energy Systems, University of Victoria; 1997.
[85] Ross Michael MD. Diversification of energy supply: prospects for emerging energy sources (Manila: Paper prepared for the Asian Development Bank's Asian Development Outlook; 2013.
[86] Rowan E Engle M, Kirby C, Kraemer T. Radium content of oil- and gas-field produced waters in the northern Appalachian Basin (USA)—summary and discussion of data. U.S. Geological Survey Scientific Investigations Report, vol. 513; 2011. 31 p.
[87] Saiers JE, Barth E. Potential contaminant pathways from hydraulically fractured shale aquifers. Groundwater 2012;50(6):826–8.
[88] Sakmar Susan L. The global shale gas initiative. Houst J Int Law 2011;33:369–417.
[89] Schmidt Charles W. Blind rush? Shale gas boom proceeds amid human health questions Environ Health Perspect 2011;119(8):348–53.
[90] Stephanie Scott. Who shale regulate the fracking industry. Villanova Environ Law J 2013;24:189–223.
[91] Selley Richard C. UK shale gas: the story so far. Mar Pet Geol 2012;31:100–109.
[92] Sioshanshi Fereidoon. Shale gas bonanza limited to North America, for now. EEnergy Informer: Int Energy Newslett 2013:2–3.
[93] Sovacool Benjamin K. The costs of failure: a preliminary assessment of major energy accidents, 1907 to 2007. Energy Policy 2008;36(5):1802–20.
[94] Sovacool BK. What Are We Doing Here? Analyzing Fifteen Years of Energy Scholarship and Proposing a Social Science Research Agenda Energy Research & Social Science 2014;1:1–29, http://dx.doi.org/10.1016/j.erss.2014.02.003.
[95] Sovacool BK, Cooper C, Parenteau P. From a hard place to a rock: questioning the energy security of a coal-based economy. Energy Policy 2011;39(8):4664–70.
[96] Sovacool BK, Saleem S, D'Agostino AL, Ramos CR, Trott K, Ong. Y. What about social science and interdisciplinarity? A 10-year content analysis of energy policy In: Goldblatt DL, et al., editors. Tackling long-term global energy problems: the contribution of social science. New York: Springer; 2012. p. 47–71.
[97] Sovacool BK, Vivoda V. Enhancing the energy security and governance of shale gas. Oil Gas Energy Law 2014. Available at: 〈http://www.ogel.org/journal-advance-publication-article.asp?key=415〉.
[98] Stevens Paul. Hydrocarbons and depletion: shale gas technology to the rescue? Clark Maxwell Lecture to the IET; 2013.
[99] Thomas Sundqvist. What causes the disparity of electricity externality estimates? Energy Policy 2004;32:1753–66.
[100] Sundqvist Thomas, Soderholm Patrik. Valuing the environmental impacts of electricity generation: a critical survey. J Energy Lit 2002;8(2):1–18.
[101] Swartz Gusti. Sierra club's breaking news on radon on fracked gas. Sierra Club Atlantic Chapter Press; 2011.
[102] Tiemann Mary, Vann Adam. Hydraulic fracturing and safe drinking water act issues: Congressional Research Service Report R41760. Washington, DC; 2012.
[103] Tollefson Jeff. Air sampling reveals high emissions from gas field. Nature 2012;482(9):139–40.
[104] U.S. Department of Energy. Office of Fossil Energy, National Energy Technology Laboratory, Modern shale gas developments in the United States: a primer. Washington, DC: DOE; 2009.
[105] U.S. Department of Energy. Secretary of Energy Advisory Board (SEAB) shale gas production subcommittee ninety-day report – August 11; 2011.
[106] U.S. EIA. World shale gas resources: an initial assessment of 14 regions outside the United States. Washington, DC: U.S. Department of Energy; 2011).
[107] U.S. EIA. Annual energy outlook 2013. Washington, DC: U.S. Department of Energy; 2013.
[108] Vengosh Avner, et al. The effects of shale gas exploration and hydraulic fracturing on the quality of water resources in the United States. Procedia Earth Planet Sci 2013;7:863–6.
[109] Wang Jinsheng, Ryan David, Anthony Edward J. Reducing the greenhouse gas footprint of shale gas. Energy Policy 2011;39:8196–9.
[110] Wang Q, Chen XN, Jha A, Rogers H. Natural gas from shale formation – the evolution, evidences and challenges of shale gas revolution in United States. Renew Sustain Energy Rev 2014;30:1–28.
[111] Westphal Kirsten. Unconventional Oil and Gas Global Consequences. SWP Comments; 2013. p. 1–8.
[112] Wiser Ryan, Bolinger Mark. 2010 Wind technologies market report. Washington, DC: U.S. Department of Energy; 2011 (June 2011. DOE/GO-102011-3322).
[113] Yin Robert K. Case study research: design and methods. London: Sage; 2003.
[114] Zou Caineng. Shale gas unconventional petroleum geology. London: Elsevier; 2013; 149–90.